Neutrino Flux Uncertainties With New HARP Data

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NuFact 06

UC Irvine, August 24-30, 2006

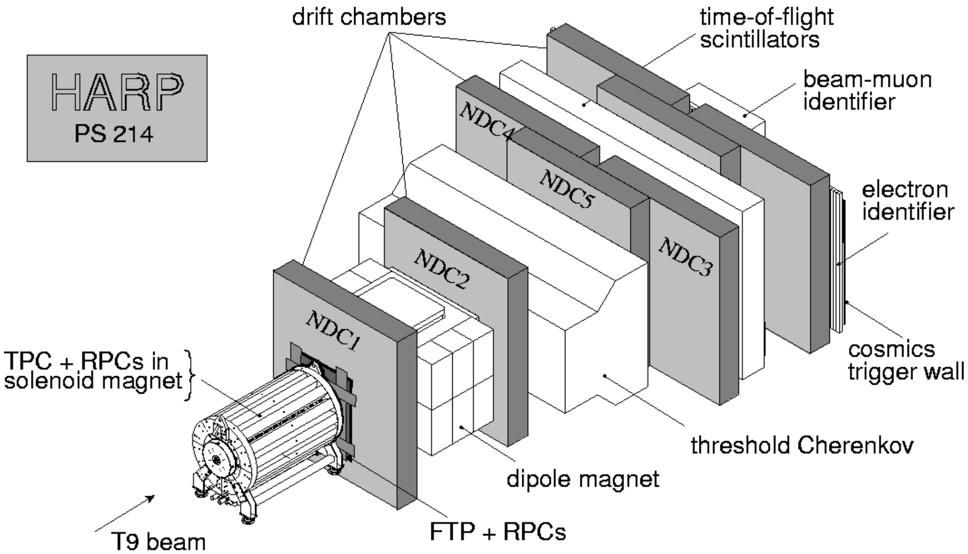
Special thanks to:
M. Hasegawa, J. Link, J. Monroe, P. Novella, D. Schmitz, H. Tanaka

HARP

- HARP: fixed target experiment for accurate and broad-range hadron production measurements in “seven dimensions”:

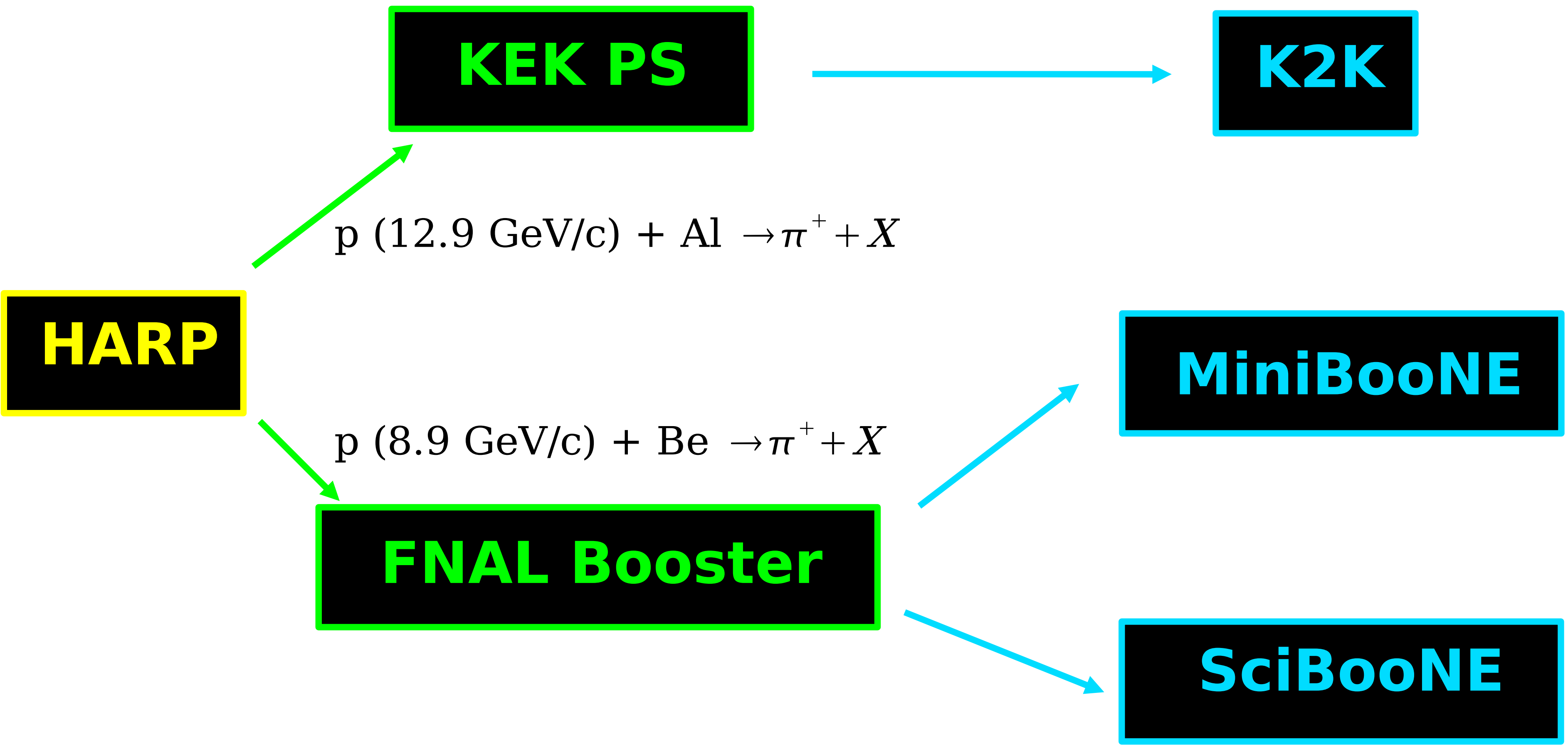
- Hadron type measured: $h = \pi^{\pm}, K^{\pm}, p$
- Production phase space covered:

  $0.5 < p_h < 8$ GeV/c, $20 < \theta_h < 250$ mrad
- Projectile type: $p, \pi^{\pm}$
- Projectile momentum: $p_{\text{beam}} = 3 - 15$ GeV/c
- Nuclear target material: $A = 1 - 200$
- Nuclear target thickness: $\lambda_{\text{int}} = 2 - 100$ %



Various Kinds of Flux Uncertainties

HARP direct input to accelerator-based neutrino experiments:



Various Kinds of Flux Uncertainties

NuFact 06 talks:

HARP → **KEK PS** → **K2K**

HARP → **FNAL Booster** → **MiniBooNE**

FNAL Booster → **SciBooNE**

HARP: Borghi, Raja, Schmitz, Soler

K2K: Kaneyuki, Hayato

MiniBooNE: Curioni, Link

SciBooNE: Wascko, Tanaka

Various Kinds of Flux Uncertainties

Most important (not only!) neutrino measurements at these exps:

HARP

KEK PS → **K2K**

ν_μ disappearance

FNAL Booster → **MiniBooNE**

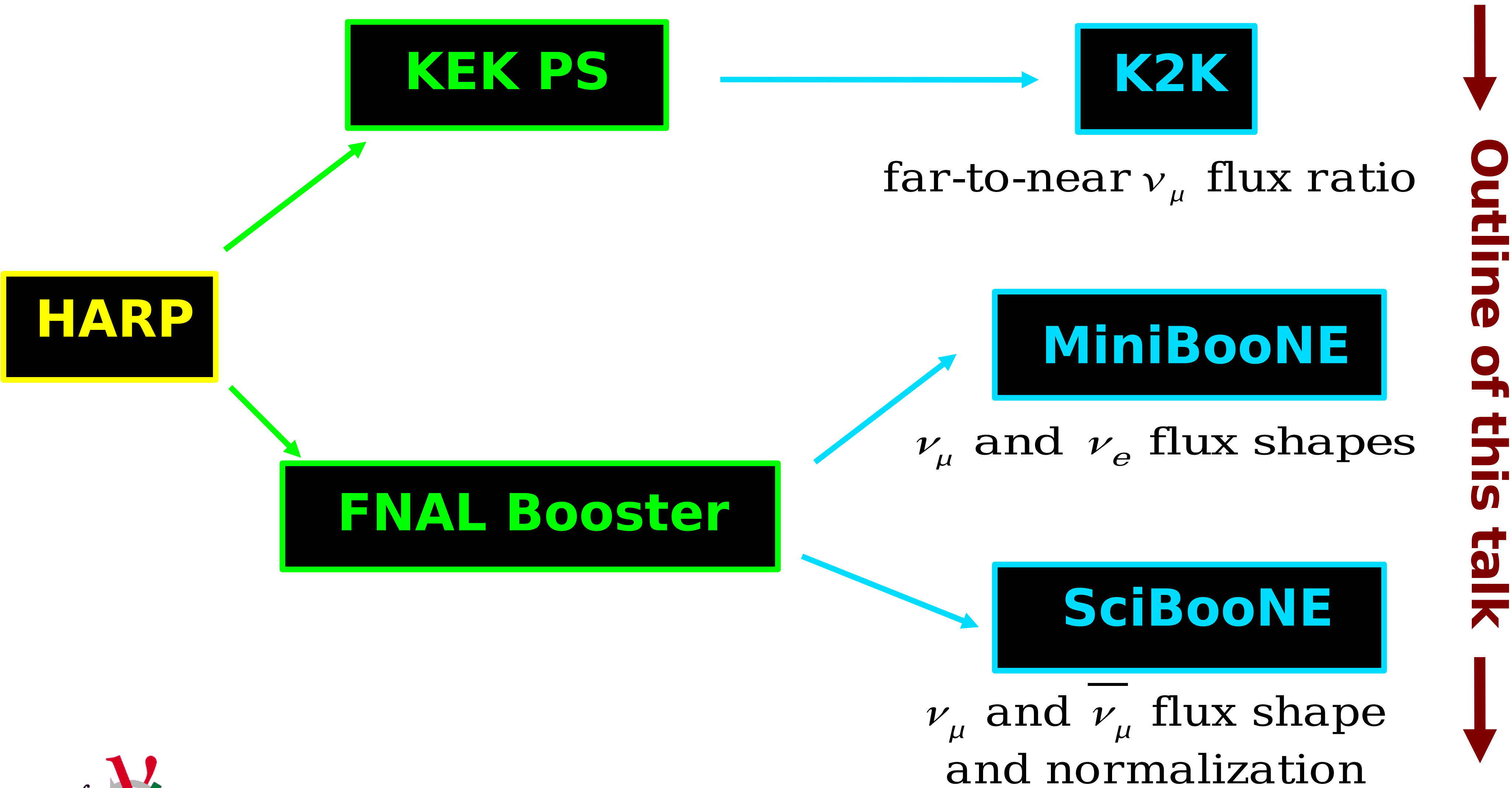
$\nu_\mu \rightarrow \nu_e$ appearance

FNAL Booster → **SciBooNE**

ν_μ and $\overline{\nu_\mu}$ cross-sections

Various Kinds of Flux Uncertainties

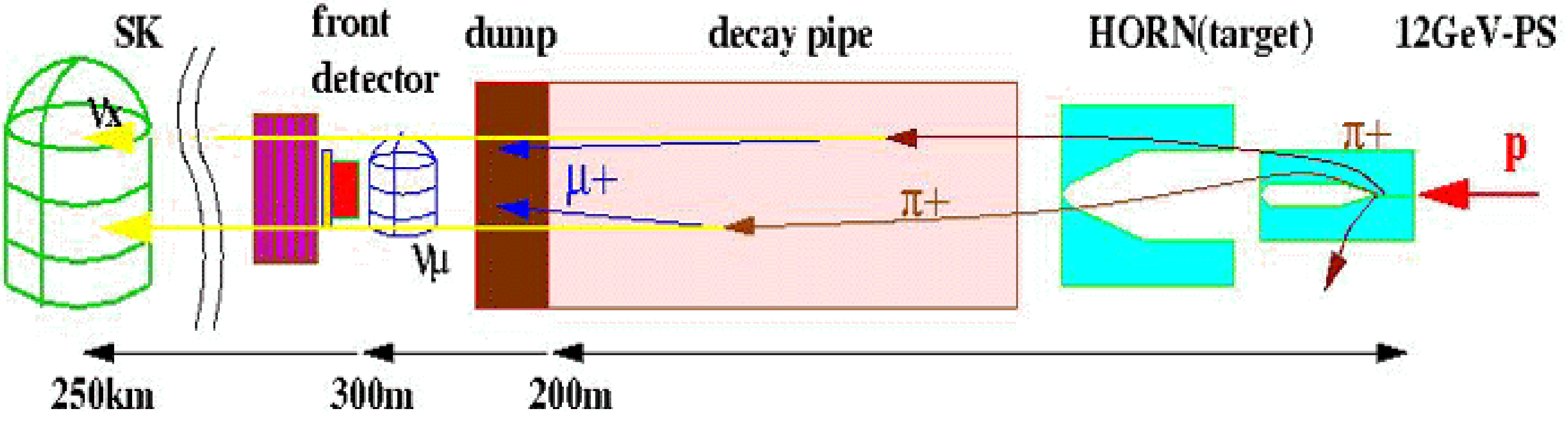
Most relevant flux uncertainties for these measurements:



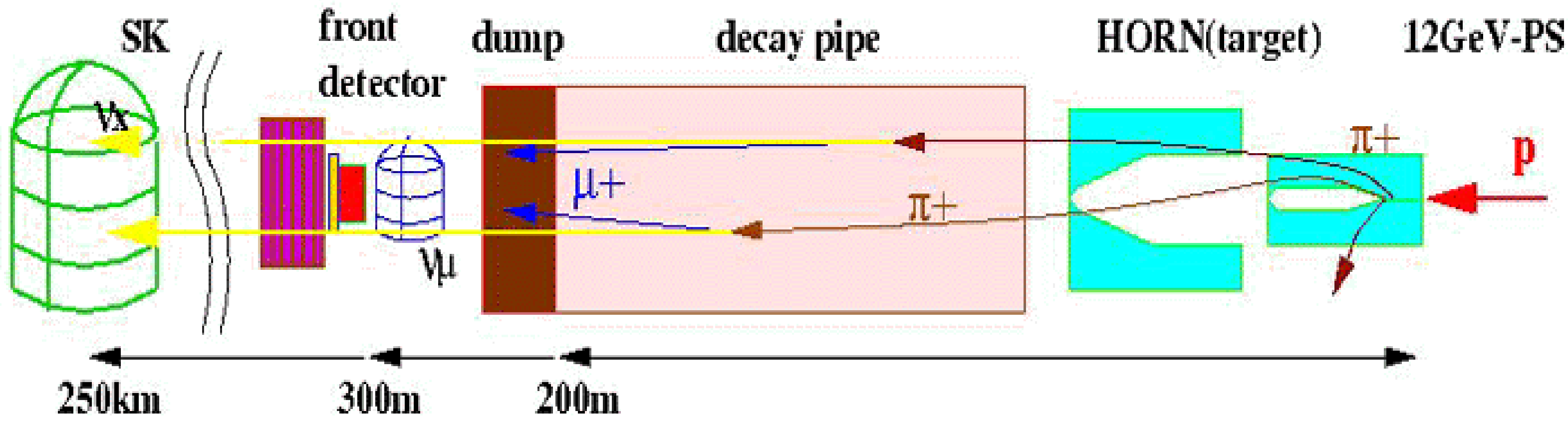
HARP & K2K Disappearance

The K2K Experiment

Goal: confirmation of atmospheric oscillations by measuring muon neutrino disappearance in a long-baseline accelerator-based experiment



K2K Disappearance Analysis



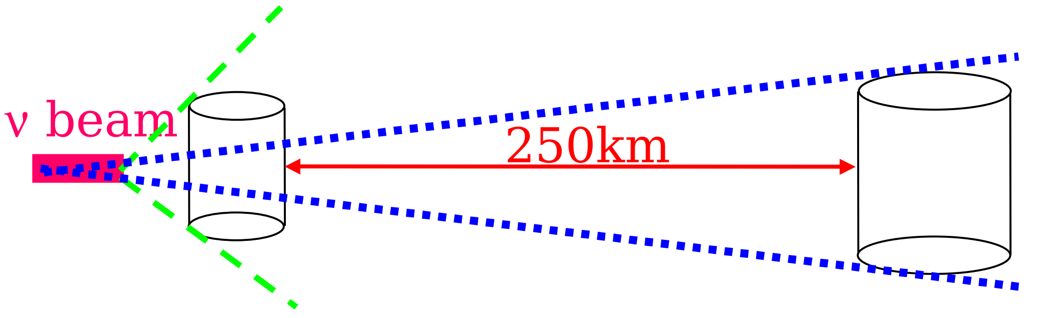
Basic analysis strategy:

- Measure unoscillated overall muon neutrino flux normalization and flux energy shape with near detectors (rate with 1KT, spectrum with 1KT+MRD+SciFi+SciBar)

- Get a muon neutrino flux prediction at the far detector for no oscillations by extrapolating the near detector measurements to the far detector, using a (energy-dependent) far-to-near ratio prediction from simulations (beam MC)

- Compare measured rate and energy shape at the far site with the no-oscillation predictions to study neutrino oscillations

K2K Far-to-Near Flux Ratio



In the absence of oscillations:

- For a point-like and isotropic neutrino source, the flux scales with distance as $1/L^2$, and F/N ratio is constant with energy
- Extended source correction for near detector: F/N ratio decreases with energy
- Different angular acceptance correction: F/N ratio increases with energy
- Overall results: non-perfect $1/L^2$ scaling, and characteristic "dip" in energy in F/N ratio, which could fake oscillations if not modelled properly!

While gross features of F/N ratio depend simply upon pion lifetime and geometry, to get the needed fine details right, knowledge of hadronic production is crucial

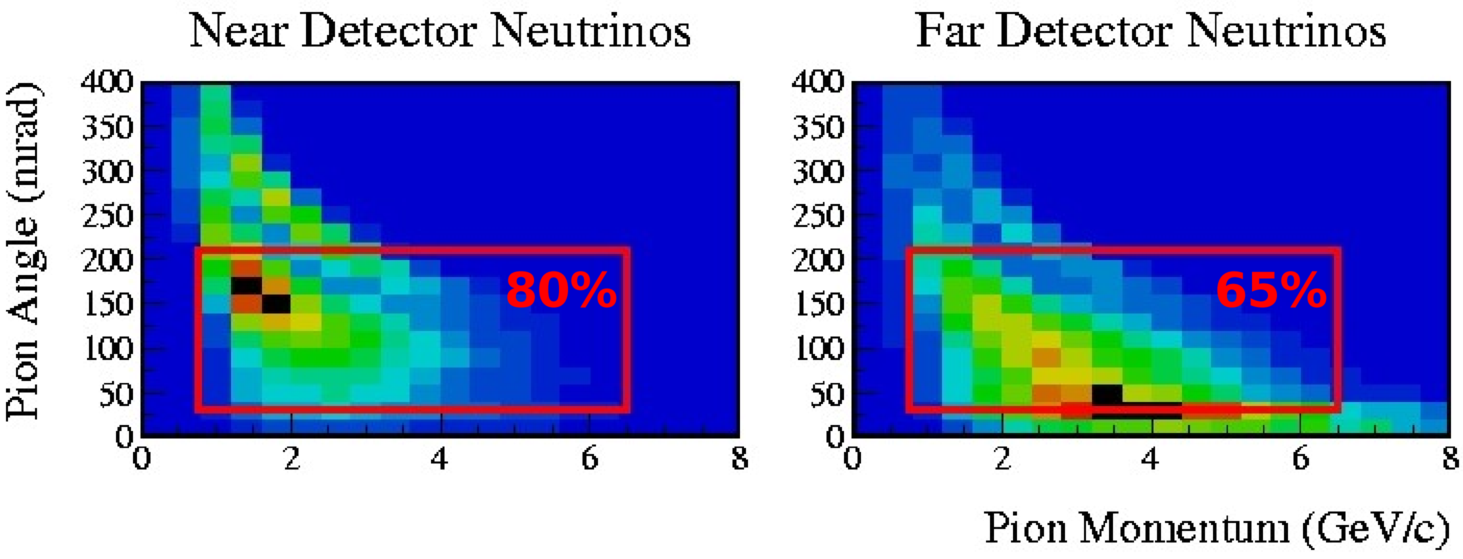
Relevance of HARP for K2K

- $\pi^+ \to \mu^+ \nu_\mu$ decays are responsible for ~97% of all the K2K neutrino flux

- HARP forward pion production result used covers:

$$0.75 < p_\pi < 6.5 \;\; GeV/c, \;\; 30 < \theta_\pi < 210 \;\; mrad$$

Good coverage of phase space of relevance to K2K



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Nuclear Physics B 732 (2006) 1–45

NUCLEAR PHYSICS B

Measurement of the production cross-section of positive pions in p–Al collisions at 12.9 GeV/c

HARP Collaboration

Abstract

A precision measurement of the double-differential production cross-section, $d^2\sigma^{\pi^+}/dp\,d\Omega$, for pions of positive charge, performed in the HARP experiment is presented. The incident particles are protons of 12.9 GeV/c momentum impinging on an aluminium target of 5% nuclear interaction length. The measurement of this cross-section has a direct application to the calculation of the neutrino flux of the K2K experiment. After cuts, 210 000 secondary tracks reconstructed in the forward spectrometer were used in this analysis. The results are given for secondaries within a momentum range from 0.75 to 6.5 GeV/c, and within an angular range from 30 mrad to 210 mrad. The absolute normalization was performed using prescaled beam triggers counting protons on target. The overall scale of the cross-section is known to better than 6%, while the average point-to-point error is 8.2%.

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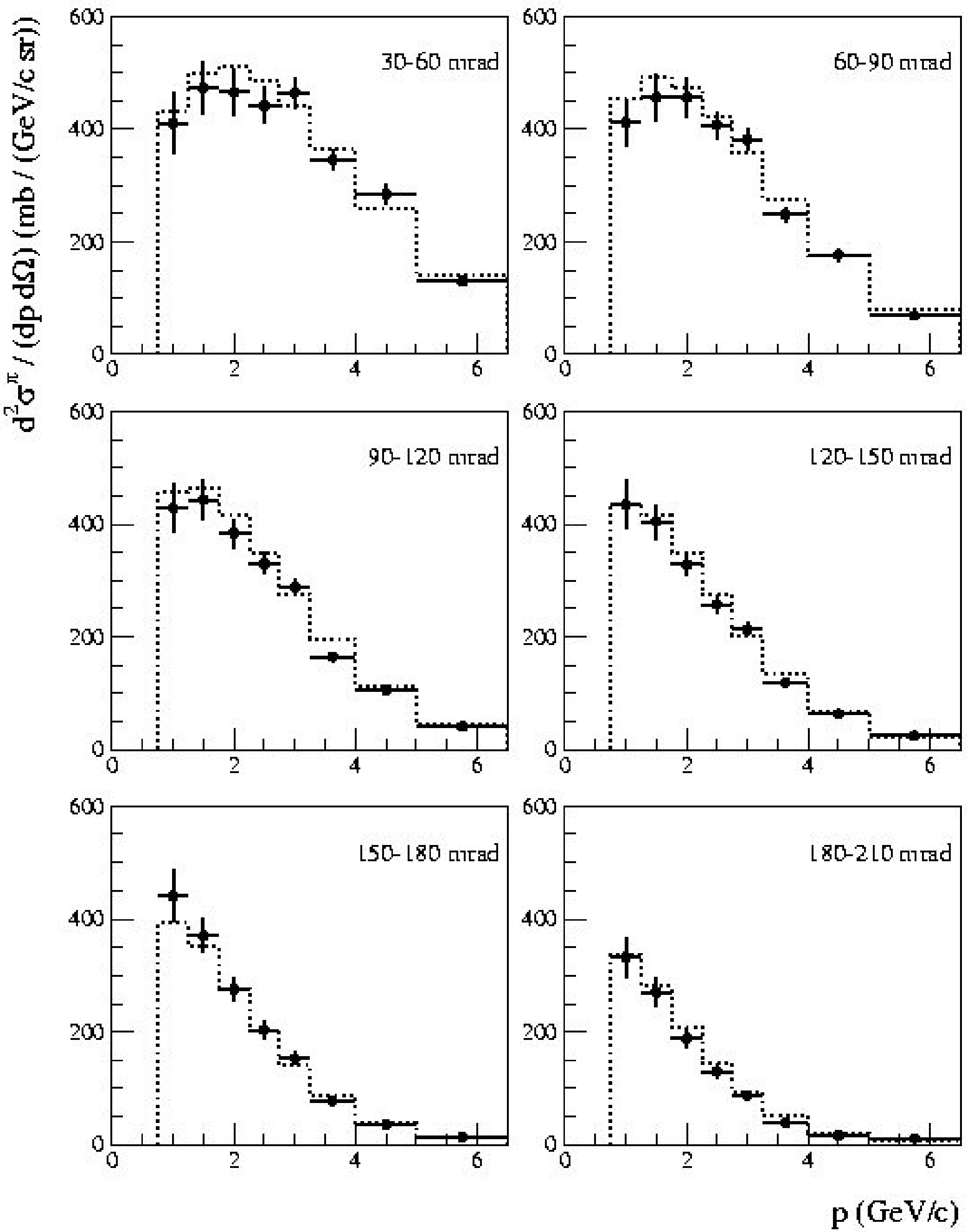
HARP Pion Results For K2K

Inclusive, double-differential π^+ production cross-section in the interactions of 12.9 GeV/c protons in a 5% λ Al target



Data points: HARP results

Dotted histogram: best-fit parametrization

Parametrization of HARP Pion Data

- HARP data on inclusive pion production fitted to Sanford-Wang parametrization:

$$\frac{d^2\sigma(p+Al\rightarrow \pi^+ + X)}{dp\,d\Omega}(p,\theta) = c_1 p^{c_2}\left(1-\frac{p}{p_{beam}}\right)\exp\left[-c_3\frac{p^{c_4}}{p_{beam}^{c_5}} - c_6\,\theta\left(p - c_7 p_{beam}\cos^{c_8}\theta\right)\right]$$

where:

X: any other final state particle

$p_{\mathrm{beam}}=12.9$: proton beam momentum (GeV/c)

p,θ: π^+ momentum (GeV/c) and angle (rad)

$d^2\sigma/(dp\,d\Omega)$ units: mb/(GeV/c sr), where $d\Omega = 2\pi\, d(\cos\theta)$

$c_1,\ldots,c_8$: empirical fit parameters

Sanford-Wang parametrization used to:

- Use HARP data in K2K beam MC (smoothing and zero acceptance extrapolation)
- Translate HARP pion production uncertainties into flux uncertainties
- Combine hadron production results, accounting for beam momentum and pion phase space effects

HARP Pion Uncertainties

Thorough systematics error evaluation performed, to quantify errors on both:

- Double-differential cross-section: $d^2\sigma^\pi/(dp d\Omega)\ (p,\theta)$. Typical error: 8.2%
- Total cross-section: $\sigma^\pi(0.75<p<6.5\ \mathrm{GeV/c}, 30<\theta<210\ \mathrm{mrad})$. Error: 5.8%

Error category	Error source	δ_{diff} (%)	δ_{int} (%)
Statistical	Al target statistics	1.6	0.3
	Empty target subtraction (stat)	1.3	0.2
	Subtotal	2.1	0.4
Track yield corrections	Reconstruction efficiency	0.8	0.4
	Pion, proton absorption	2.4	2.6
	Tertiary subtraction	3.2	2.9
	Empty target subtraction (syst)	1.2	1.1
	Subtotal	4.5	4.1
Particle identification	PID Probability cut	0.2	0.2
	Kaon subtraction	0.3	0.1
	Electron veto	2.1	0.5
	Pion, proton ID correction	2.5	0.4
	Subtotal	3.5	0.7
Momentum reconstruction	Momentum scale	3.0	0.3
	Momentum resolution	0.6	0.6
	Subtotal	3.2	0.7
Overall normalization	Subtotal	4.0	4.0
All	Total	8.2	5.8

Dominant errors: overall normalization, momentum scale, secondary interactions

K2K Flux Uncertainties

Primary beam optics:	1. mean centering 2. mean injection angle 3. spread/angular divergence
Primary hadronic interactions:	4. interaction length **5. pion prod. multiplicity and kinematics** 6. kaon prod. multiplicity
Secondary hadronic interactions:	7. interaction length, tertiaries multiplicity and kinematics
Horn magnetic fields:	8. field strength 9. field perturbations in azimuth

Current K2K strategy:

- **All** E_ν: HARP pion production assumed to estimate all uncertainties. HARP errors assumed for largest systematics, i.e. pion production

Pre-HARP assumptions, providing powerful cross-check on HARP:

- E_ν**>1 GeV:** use in-situ (PIMON) measurement of pion distributions after horns
- E_ν**<1 GeV:** use π^+ prod. uncertainties only, from Cho-CERN parametrization of p+Be→$\pi^+ + X$ data, with $Be \to Al$ target nuclear rescaling (x2 on average)

K2K Flux Uncertainties

Error Category	Error Source	Far/Near Ratio Uncertainty (%)
Primary Beam Optics	Mean centering	<0.1
	Mean aiming	<0.1
	Spread and angular divergence	0.8
	Sub-total	**0.8**
Primary Hadronic Int.	Interaction rate	0.6
	Multiplicity and kinematics of π^+ prod.	1.4
	Multiplicity of $K^\pm, K_0, \overline{K}_0$ production	0.2
	Sub-total	**1.6**
Secondary Hadronic Int.	Rate, tertiary multiplicty and kinematics	0.7
	Sub-total	**0.7**
Horn Magnetic Fields	Magnetic field strength	0.5
	Azimuthal field perturbations	0.3
	Sub-total	**0.6**
All	**Total**	**2.0**

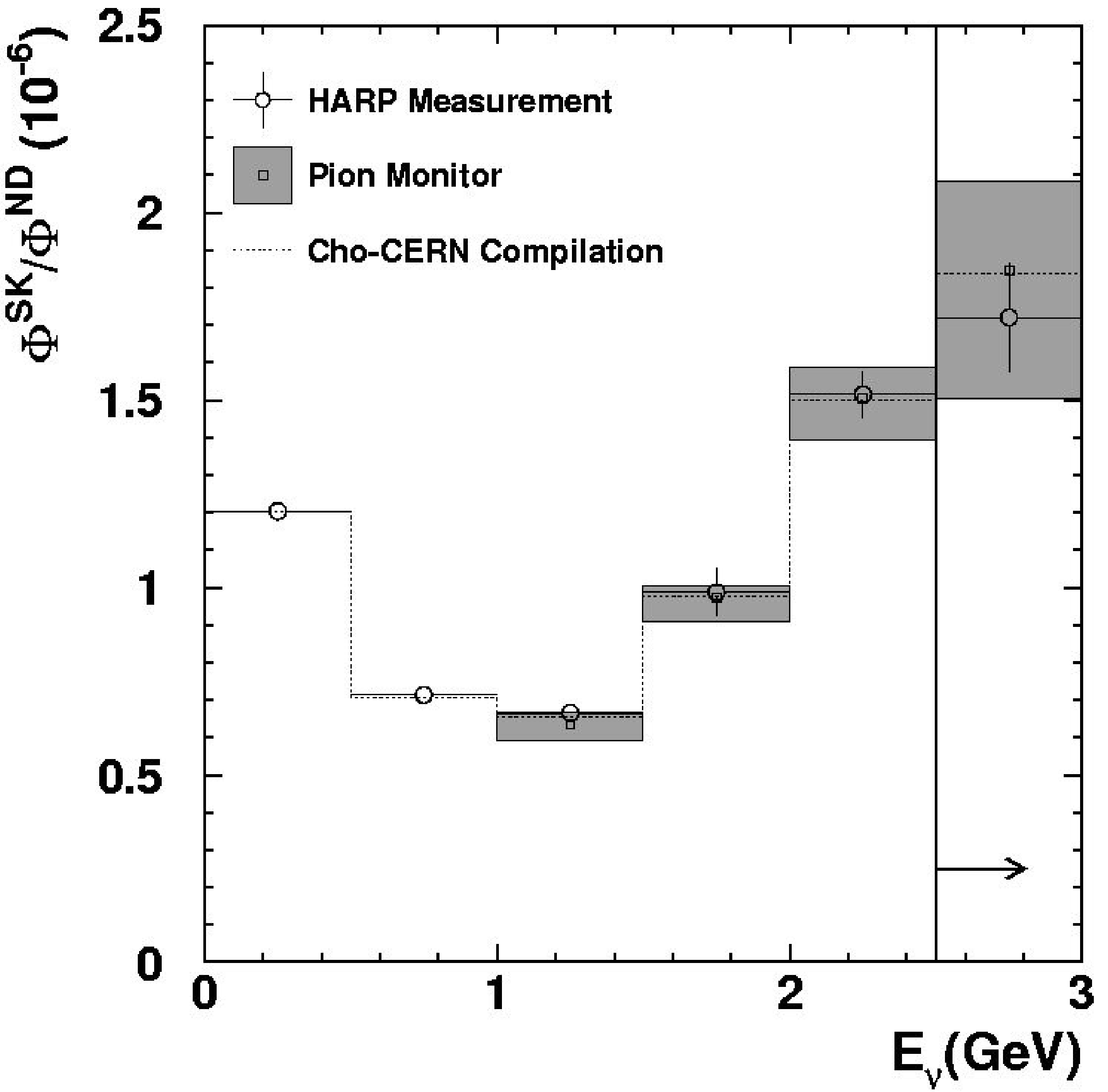
- 2% uncertainty on total F/N ratio. Uncertainty tends to increase with energy

- Dominant error: HARP error on pion production in interactions of 12.9 GeV/c p on Al

K2K F/N Ratio Prediction

- Far-to-near flux ratio predictions from HARP, Cho-CERN, PIMON

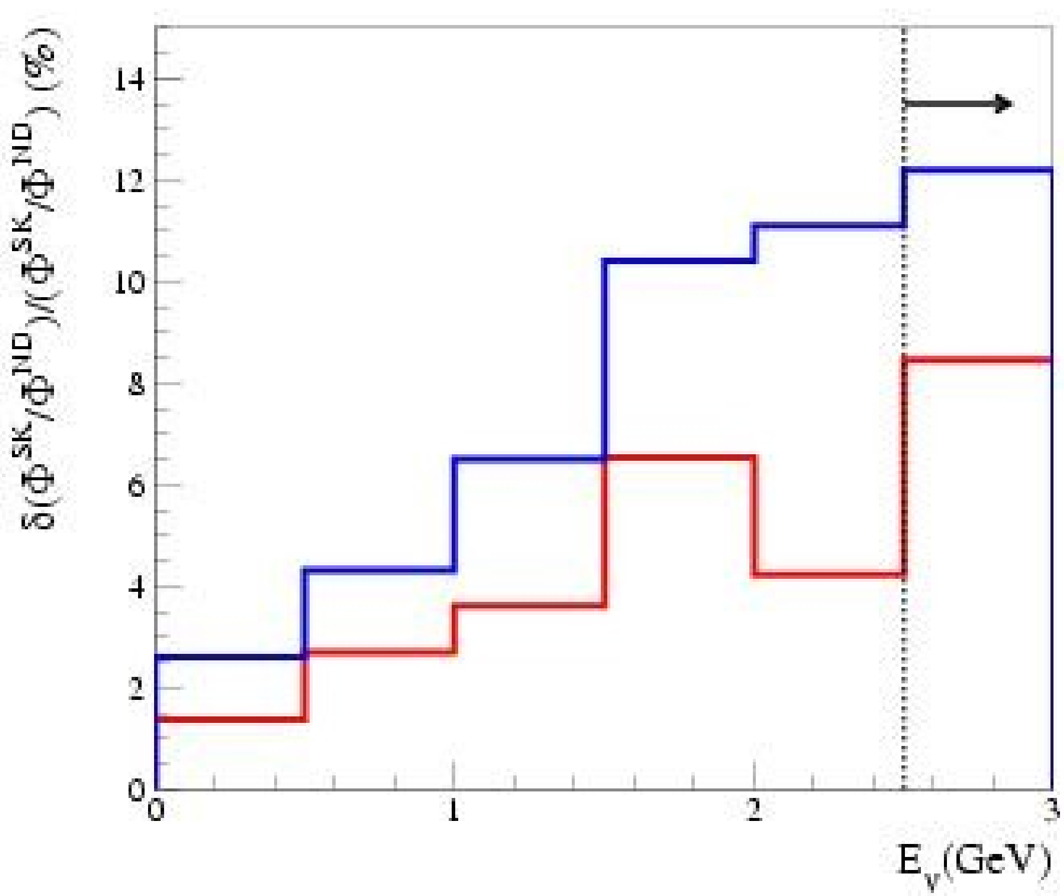
- Three predictions are consistent with each other



Comparison With Previous Uncertainty Assumption

<1 GeV: Cho/CERN errors

>1 GeV: PIMON errors



All energies: HARP (plus others) errors

Blue: previous error estimate

Red: HARP-based evaluation

HARP: almost **factor of 2 error reduction** across all energies, compared to previous assumptions

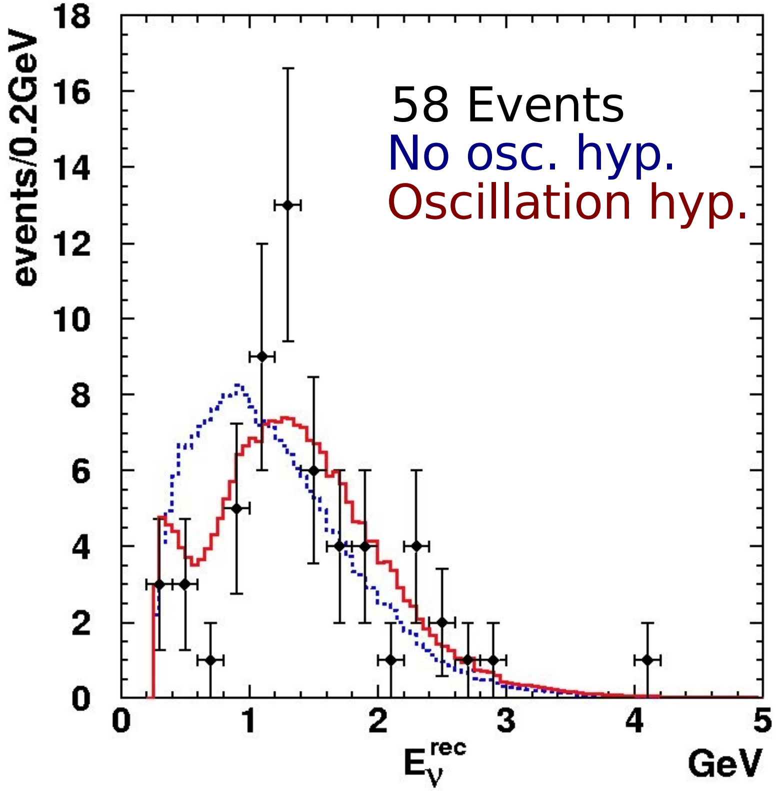
K2K Disappearance Result

Sensitivity to oscillations: from rate suppression and spectrum distortion informations

- Two different samples used:

Rate:
- Use all beam-induced events fully contained at SK
- Measure **112**, predict **158.1 + 9.2 – 8.6** for no osc.
- Dominant errors:

> • Statistical
> • 1KT+SK fiducial volume (5% norm. error)
> • Near-to-far flux extrapolation (reduced to 3% by HARP)



Spectrum:
- Use only CCQE candidate events ("1 ring events"), for better neutrino energy reconstruction
- Dominant errors:

> • Statistical
> • SK energy scale (2% uncertainty)

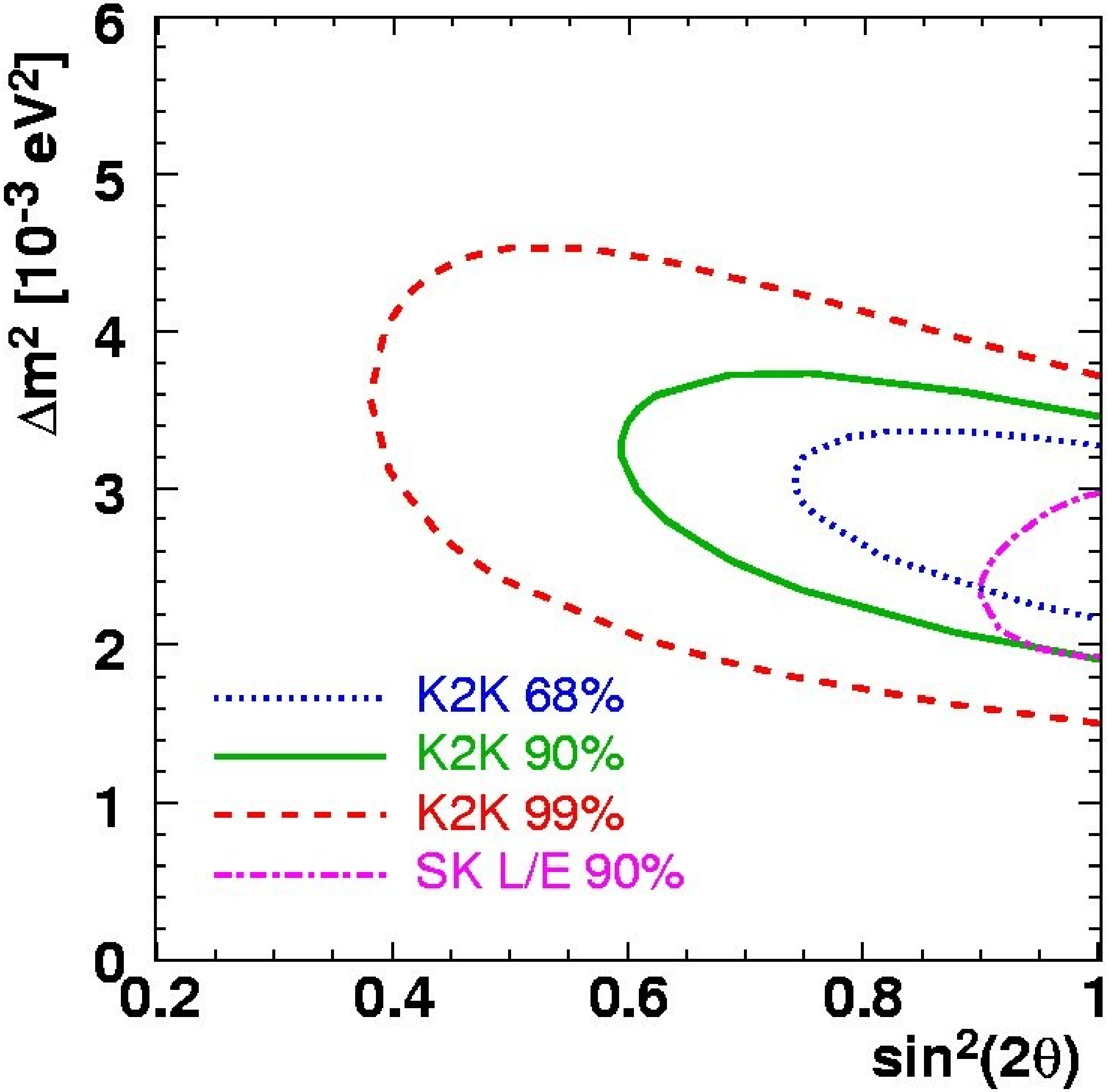
Significance of Oscillations

Null oscillation probability: probability that the null oscillation and the osc. hypotheses describe K2K data equally well. Can be converted into number of sigmas

Errors Considered	**Significance (# sigmas)**		
	Rate Only	Spectrum Only	Combined
Stat. Only	3.9	3.1	4.9
Stat. + HARP F/N Ratio Syst.	3.7	3.0	4.7
Stat. + Fiducial Vol. Syst.	3.6	3.1	4.6
Stat. + Energy Scale Syst.	3.9	2.9	4.8
Stat. + All Syst.	**3.4**	**2.9**	**4.3**

- Significance of oscillations: 4.3 sigma (rate-only: 3.4, spectrum-only: 2.9)
- K2K is statistics-limited: if systematics were negligible, 4.9 sigma signif. instead
- Main syst. error on rate-based oscillation measurement is fiducial volume and not F/N
- HARP has provided direct cross-check on critical aspect the K2K oscillation analysis

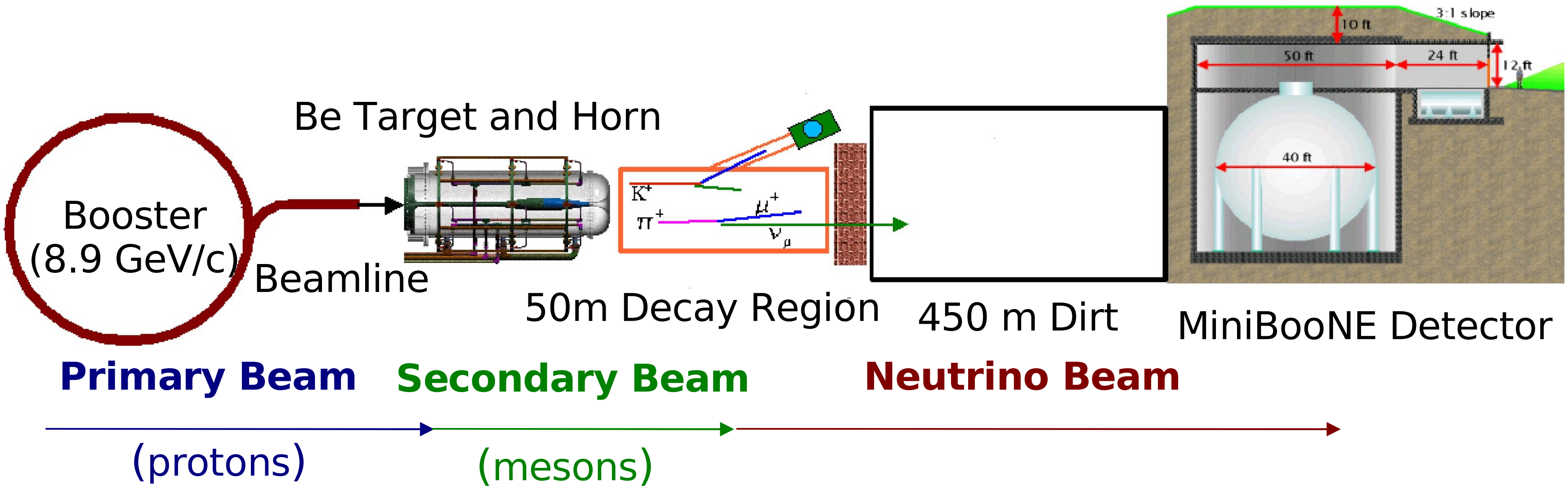
Measurement of Oscillation Parameters



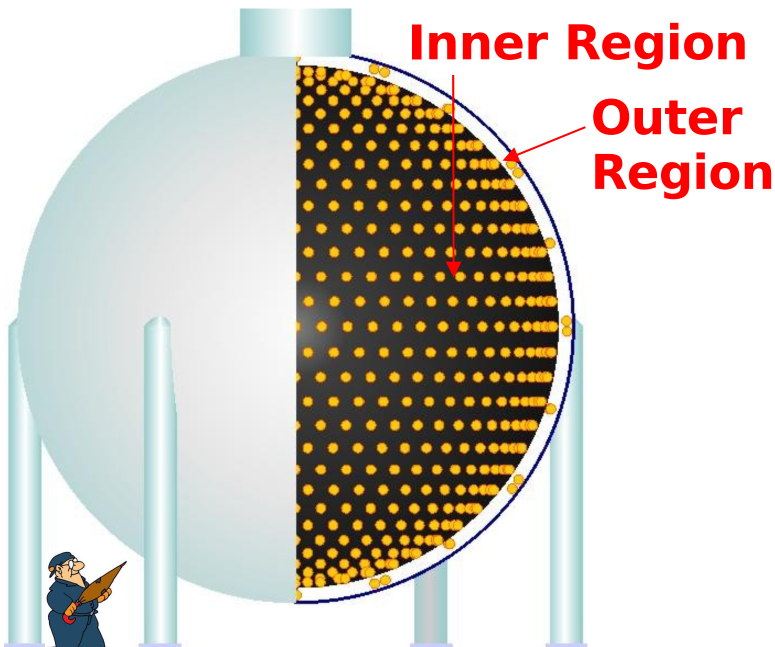
K2K compatible with SK and MINOS (not shown)

HARP & MiniBooNE Appearance

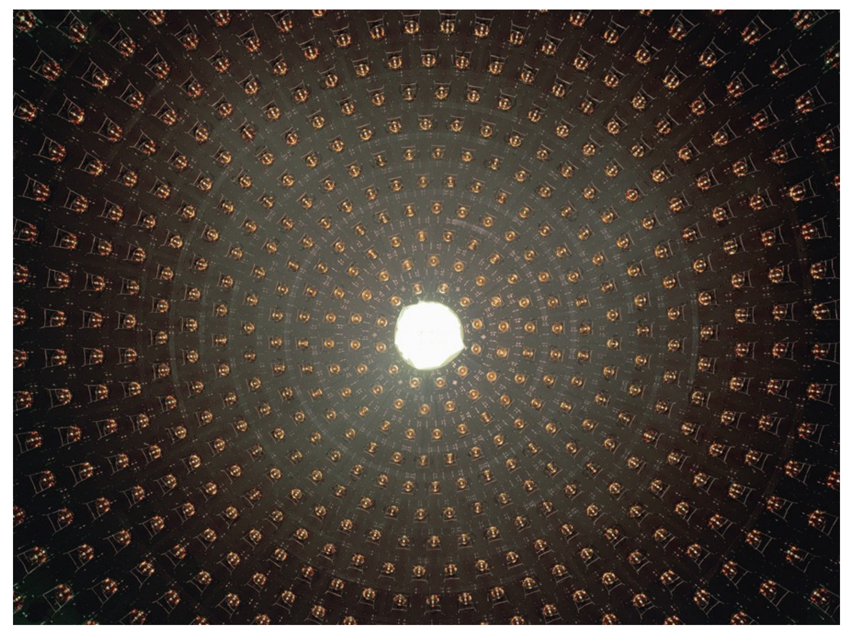
MiniBooNE



Booster
(8.9 GeV/c)
Beamline
Be Target and Horn
K+
π+
μ+
νμ
50m Decay Region
450 m Dirt
MiniBooNE Detector
3:1 slope
10 ft
50 ft
24 ft
12 ft
40 ft
Primary Beam
(protons)
Secondary Beam
(mesons)
Neutrino Beam



Inner Region
Outer
Region

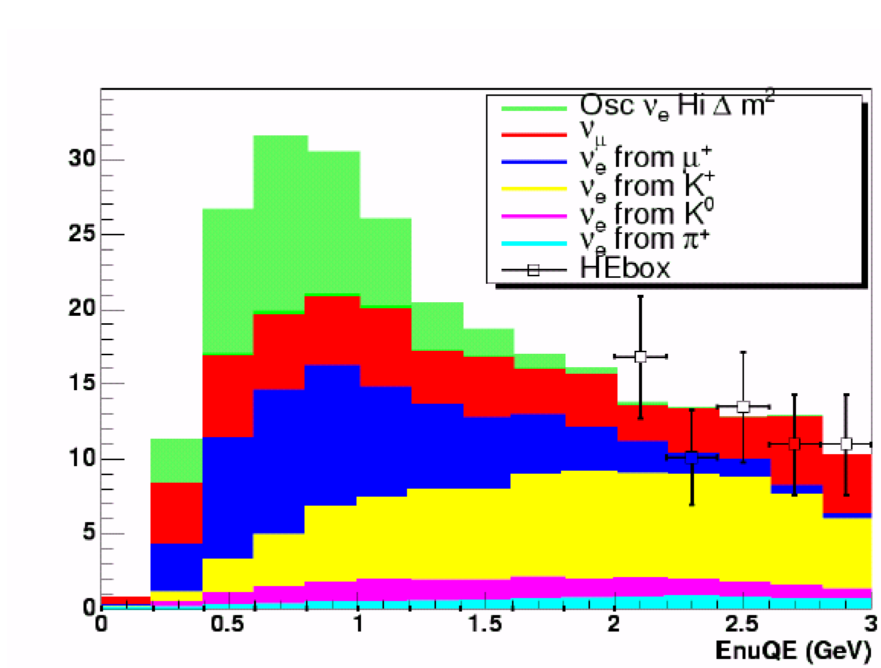


MiniBooNE $\nu_\mu \to \nu_e$ Analysis

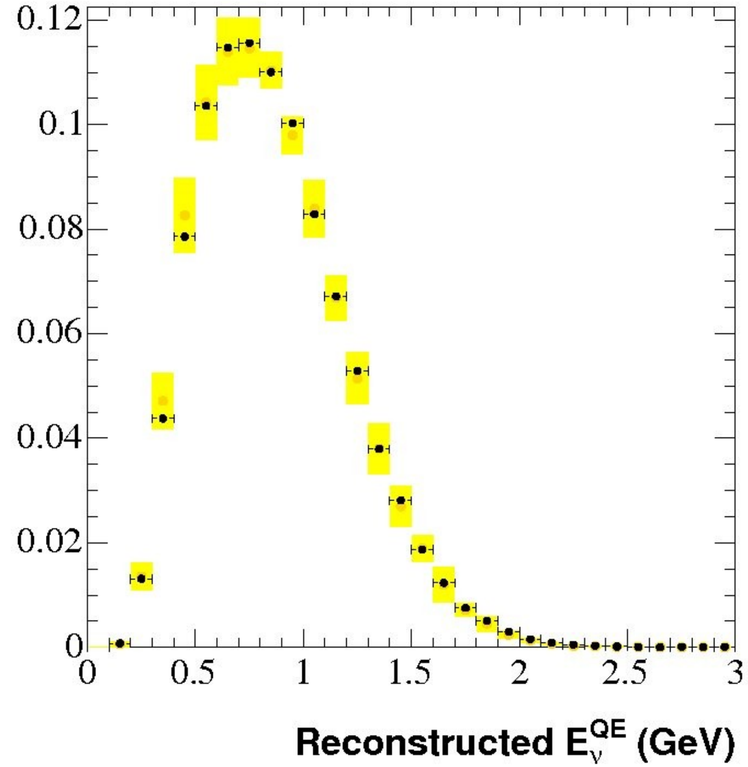
- Goal: confirm or refute the LSND $\overline{\nu_\mu} \to \overline{\nu_e}$ result in a definitive and independent way

- Method: combined fit to ν_e CCQE and ν_μ CCQE samples in bins of reconstructed neutrino energy

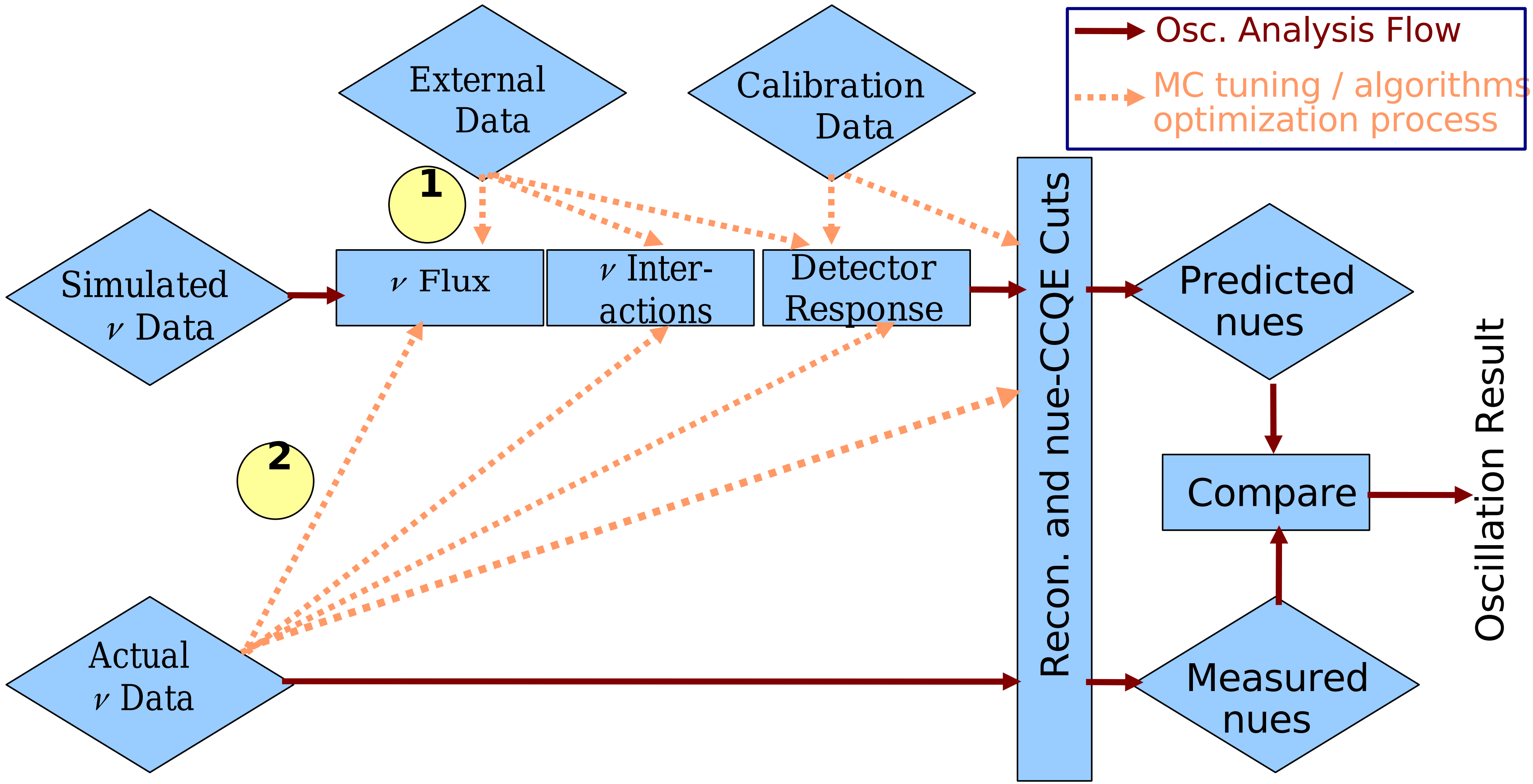
ν_e CCQE sample



ν_μ CCQE sample



MiniBooNE $\nu_\mu \rightarrow \nu_e$ Analysis

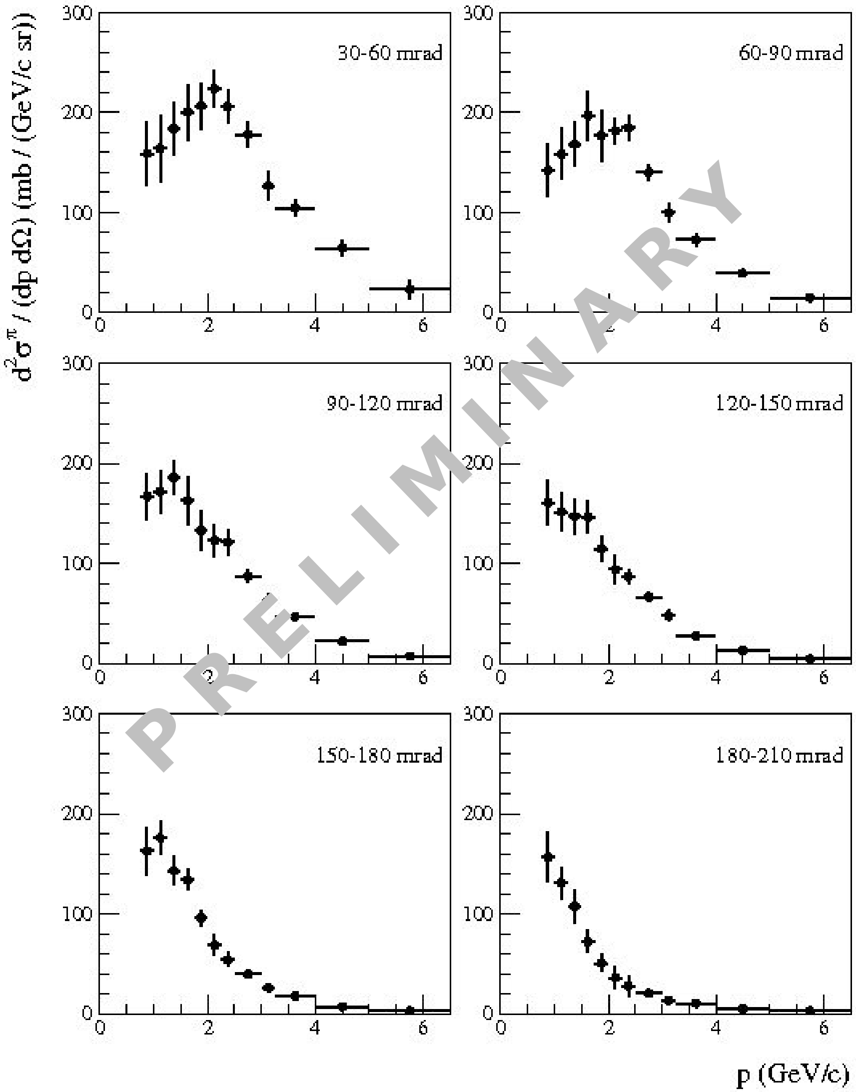


1. π^+ and K^+ data from HARP and other hadron production experiments for energy shape of ν_μ and ν_e flux predictions

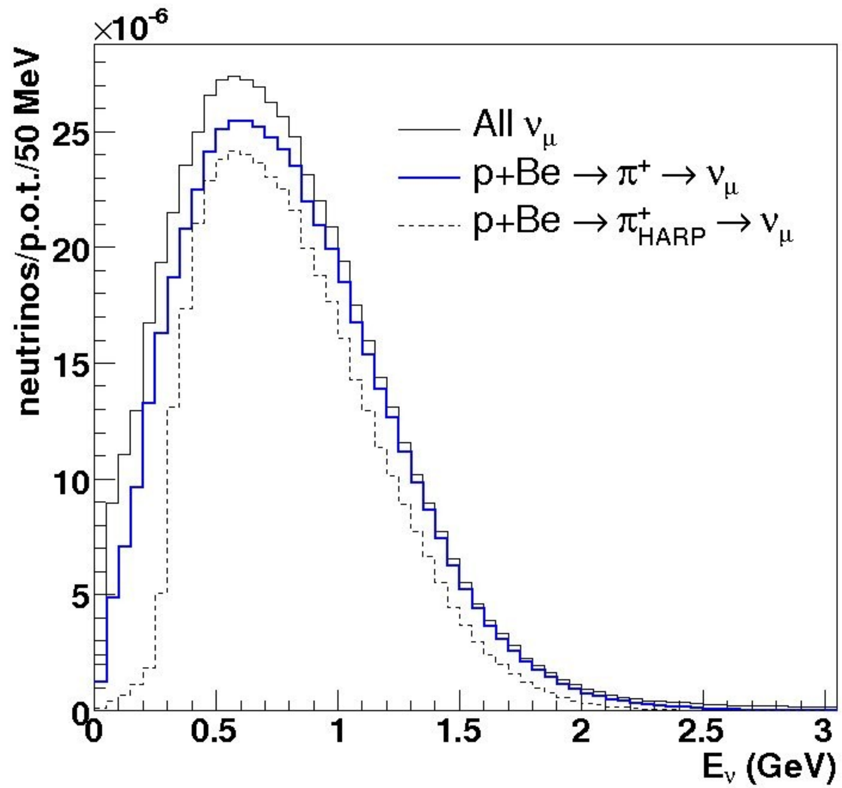
2. ν_μ CCQE data: ν_μ flux and ν_e from μ decay flux normalizations
High-energy ν data: ν_e from K decay flux normalization

HARP Pion Results For BooNE

Inclusive, double-differential π^+ production cross-section in the interactions of 8.9 GeV/c protons in a 5% λ Be target



- Large acceptance of pions of interest for BooNE:



- Similar stat and syst errors as published Al result

Muon And Electron Neutrino Flux Shape Uncertainties

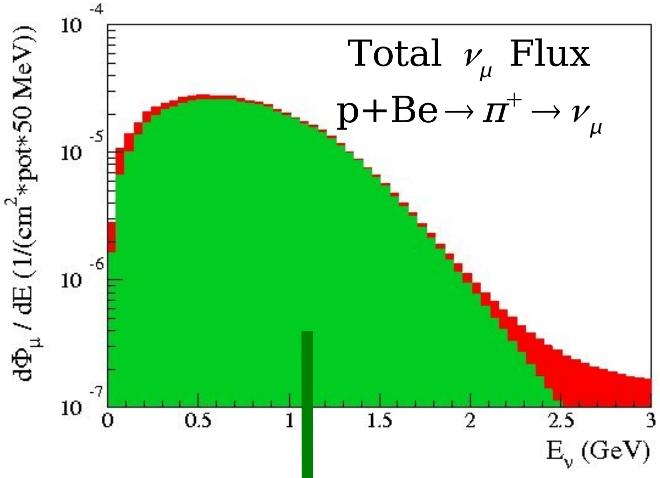
- Mostly determined by π^+ and K^+ production kinematics. Other uncertainties (not accounted for here) may have non-negligible effect on shape, e.g. hadronic interaction rates and horn focusing
- Pion production data used for flux predictions (similar to K2K procedure)

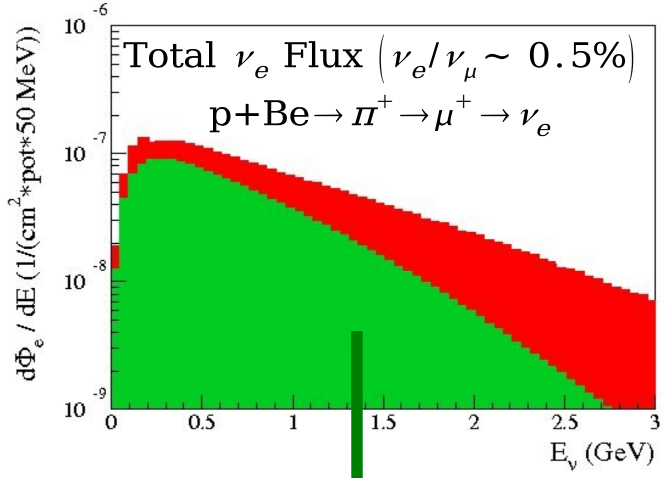
Proton Beam Momentum (GeV/c)	Pion Phase Space $\theta_{\pi,min}$ (mrad)	$\theta_{\pi,max}$ (mrad)	$p_{\pi,min}$ (GeV/c)	$p_{\pi,max}$ (GeV/c)	Data points	Experiment
12.3	42	331	0.60	5.4	71	BNL E910
6.4	71	353	0.60	4.2	29	BNL E910
8.9	30	210	0.75	6.5	72	CERN HARP

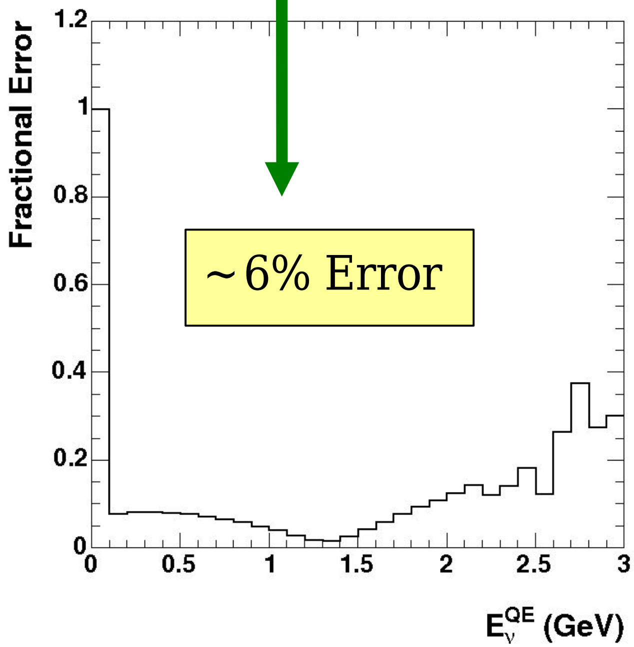
- Older, single-arm spectrometers currently used to simulate K^+ production

$\rightarrow$ Will incorporate HARP K^+ measurement when available

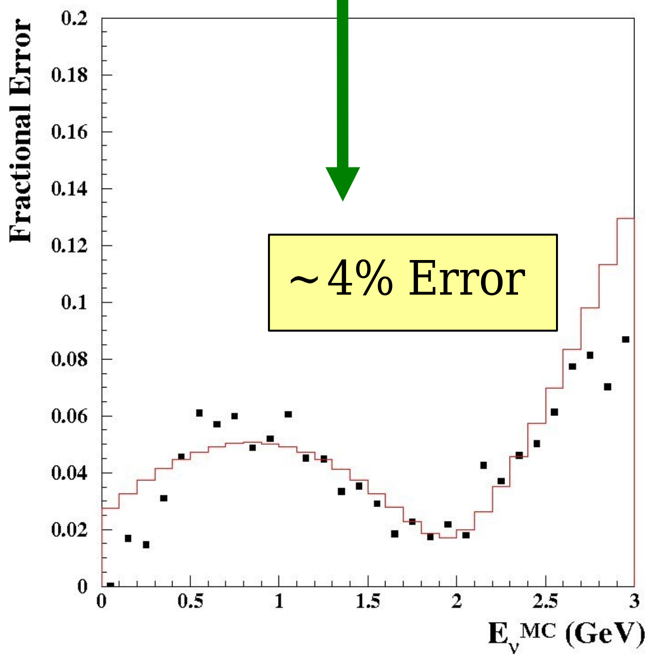
Pion Production Flux Uncertainties







~6% Error



~4% Error

HARP & SciBooNE Cross-Sections

SciBooNE

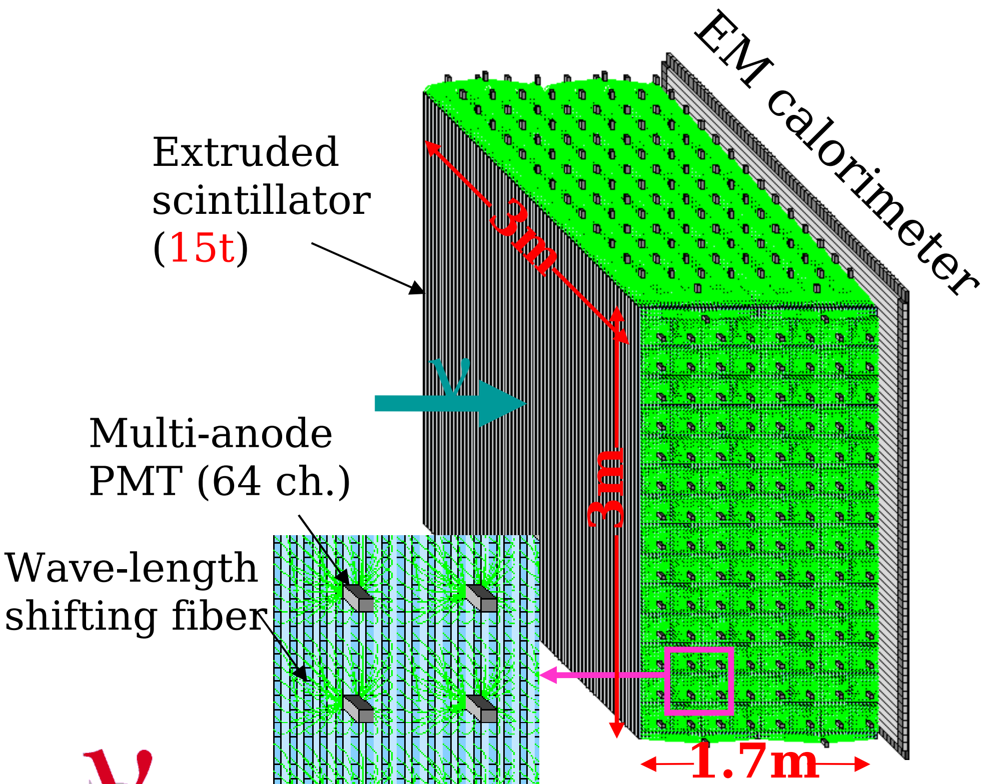
Relocate SciBar detector from KEK (Japan) to Booster Beamline at FNAL (USA)

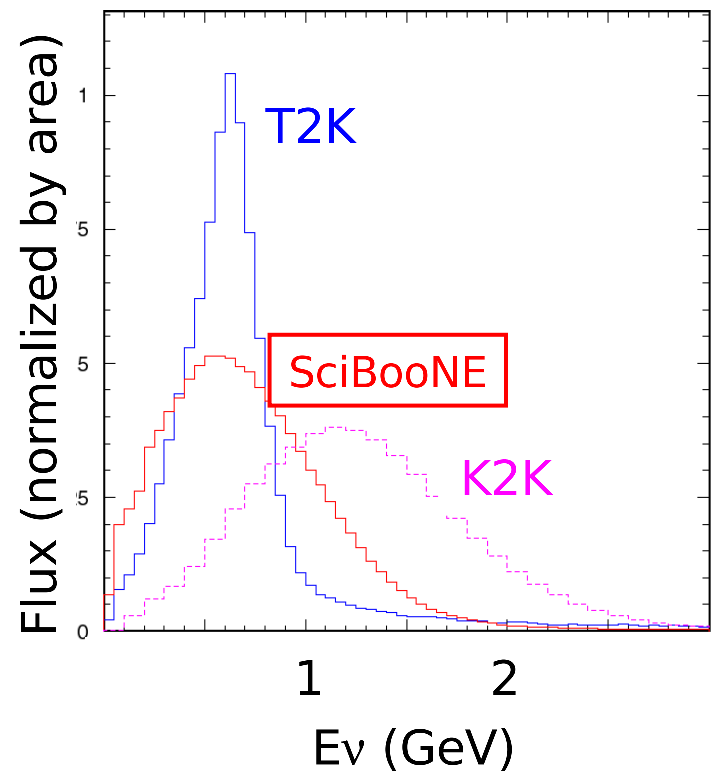
SciBar Detector:

- Fine segmentation (2.5x1.3 cm^2)
- Fully active (~10 ton fiducial)
- Excellent tracking and PID capabilities

Booster Beam:

- Excellent match in energy with T2K
- Very intense (x10 K2K)
- Neutrinos and antineutrinos
- Well understood (-> HARP)





SciBooNE Cross-Sections

- Next generation oscillation experiments require precision neutrino scattering data
- Some T2K examples:

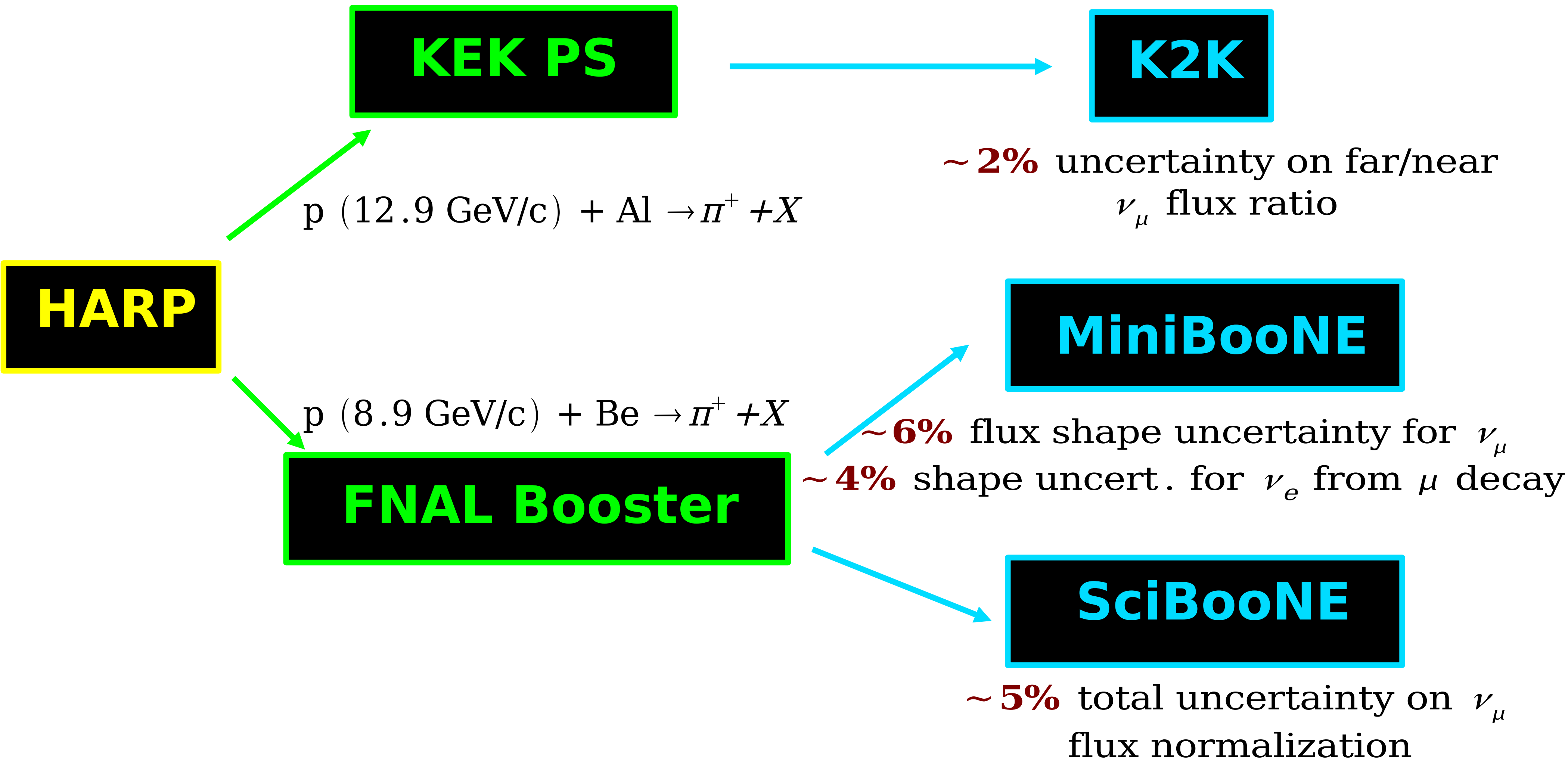
T2K Oscillation Searches	SciBooNE Cross-Sections Needed
ν_μ disapp. in phase I $\left(\theta_{23}, \Delta m^2_{23}\right)$	ν_μ CC-1π^+ production, main background to ν_μ CC-QE signal
$\nu_\mu \to \nu_e$ appearance in phase I $\left(\theta_{13}\right)$	ν_μ NC-1π^0 production, main ν_μ misID background to ν_e CC-QE signal
$\nu_\mu \to \nu_e$ .vs. $\overline{\nu_\mu} \to \overline{\nu_e}$ in phase II $\left(\delta\right)$	$\overline{\nu_\mu}$ CC-QE xsec compared to ν_μ CC-QE one, to understand $\overline{\nu_\mu} \to \overline{\nu_e}$ .vs. $\nu_\mu \to \nu_e$ signals

Muon Neutrino Flux Normalization Uncertainties

Uncertainty Source	Parameters Variations	Muon Neutrino Flux Normalization Uncertainty (%)
Protons on target counting	δN_{pot}=2%	2.0
Beam Focusing	Focusing strength and position	0.8
p-Be total cross-section	$\sigma_{\mathrm{tot}} = (285 \pm 15)$ mb	0.8
p-Be inelastic cross-section	$\sigma_{\mathrm{ine}} = (212.4 \pm 5)$ mb	1.2
p-Be quasi-elastic cross-section	$\sigma_{\mathrm{qel}} = (34.9 \pm 20)$ mb	2.5
Elastic scattering model	$\beta_{\mathrm{ela}} = (70 \pm 10)\ (\mathrm{GeV/c})^{-2}$	0.4
Quasi-elastic scattering model	$\beta_{\mathrm{qel}} = (10 \pm 3)\ (\mathrm{GeV/c})^{-2}$	1.7
π^+ production model	S-W parameters	1.8
K^+ production model	S-W parameters	0.9
Horn current	$I = (174 \pm 5)$ kA	2.0
All		**4.9**

- About 5% uncertainty on total ν_μ flux normalization (PRELIMINARY!)
- When available, will use HARP measurement of p,π interactions in thick target to firm up uncertainty estimate
- Will also use HARP π^- prod. measurement for $\overline{\nu}_\mu$ flux normalization uncertainty

Flux Uncertainties With New HARP Data



Conclusions

- A precise study of neutrino oscillations and neutrino interactions requires a precise knowledge of neutrino production

  - HARP pion production measurements have started to fill an important gap for accurate neutrino flux predictions. Examples discussed:

    K2K muon neutrino disappearance
    MiniBooNE electron neutrino appearance
    SciBooNE muon neutrino cross-sections

- More HARP data for accurate flux predictions coming:

  K^+ production data
  p,π interactions in thick targets
  π^- production data

- More HARP data for flux optimization (NuFact): S. Borghi's talk